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Working Group Report: Design Capture

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To understand what research and development is required to support design capture it is important to understand the goals of design capture. We have always wanted to capture the design of artifacts–the specifics that allow replicating (i.e., manufacturing) the artifact. It is now clear that we must also capture a wide range of information on the design process, much more than just the outcome of decisions made during the process. Rather than merely describing the designed artifact, the entire process of using tools to produce the design must be captured. Knowledge about the design process is crucial to completing a design, to facilitating communication about the design, to reusing the design in future development cycles, redesigning, and to dealing with issiues throughout the product lifecycle

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1. OVERVIEW

To understand what research and development is required to support design capture it is important to understand the goals of design capture. We have always wanted to capture the design of artifacts–the specifics that allow replicating (*i.e.*, manufacturing) the artifact. It is now clear that we must also capture a wide range of information on the design process, much more than just the outcome of decisions made during the process. Rather than merely describing the designed artifact, the entire process of using tools to produce the design must be captured. Knowledge about the design process is crucial to completing a design, to facilitating communication about the design, to reusing the design in future development cycles, to redesigning, and to dealing with issues throughout the product lifecycle.

The minimum that must be captured is the steps in the process, the time stamps of those steps, and the inputs and outputs of design decisions. Additional information, to be discussed later in this report, includes knowledge about the issues that were under study, the alternatives that were considered, the participants in the decision process, and many other considerations. Because it is difficult to predict during design what information will be needed at a later time, it is (probably) desirable to err in the direction of recording more information rather than less. This trend toward an information-rich design record needs to be accompanied by tools for providing filtered and multiple alternative views of the information captured.

Information about the design process and about the resulting artifacts must be expressed in a form that meets a number of *requirements:*

1. The representation must capture information needed for communicating and sharing between both humans and automated agents.
2. It must facilitate assessment and handling of trade-off choices and negotiations over design alternatives.
3. It must model the information needs of organizations over the entire product lifecycle.

Furthermore, the design representation must meet these requirements in a manner that recognizes that design occurs in a social setting. Design capture must record the designers' constructive contributions without impeding the designers' thought processes and without inhibiting the casual and conjectural nature of many design conversations. Privacy, control of access to information, and representation of the degree of commitment to design rationales are key issues. To understand how to do this effectively, we need more ecologically valid studies of real design. These studies need to focus on content, helping us better understand what information is used and how it is used. To support them, we need to work on instrumentation of design systems and techniques to help collect data. In particular, we need to collect data to enable the rigorous analysis of failures. This is an interdisciplinary enterprise; design capture environments need to be designed with concurrent contributions from social scientists as well as mechanical engineers, electrical engineers, and computer scientists.

Our belief is that the work needed to meet these requirements can be divided into four primary research topics:

• *Content and context*: What information needs to be recorded in the representation of a design

about the design, the design process, and the human context in which decisions were made? What is the cost of design capture and what can be done to make it acceptable to the participants?

- *Media for entering and displaying design information*: What low-level user interface techniques (devices and device drivers) can be applied to maximize the ease of use and unobtrusiveness of design capture systems?

- *Paradigms for elicitation and communication:* What high-level user-interface paradigms governing the interactions between people and systems can be used to maximize the informativeness of human-machine communications in design capture systems?

- *Computer representation and enabling technologies:* What mechanisms for storing and manipulating knowledge are needed as the basis of a design capture repository and what infrastructure is required for transmitting and sharing the contents of such repositories within and across organizations?

The balance of the report consist of four sections. Each section addresses one of these topics. In each case we offer a research plan that identifies both short-term results and long-term objectives. We also attempt to assess each issue in the plan with respect to the problem addressed, the utility to real customers, the feasibility of the goals, and the time frame in which results are expected.

Research Strategy

Implicit in all of the proposals included in the report is an understanding, shared by the members of the Working Group, about a strategy for the transfer into practice of research in design capture. That strategy is to insert modules, or "wedges," with value-added features into existing design processes and then utilize hooks designed into those modules to incrementally introduce new features that effect even bigger changes. This strategy has important implications from the point of view of research methodology and research support. *Work on design capture must be empirically driven.* Affiliation with real users is an essential requirement. Research support must enable and require the creation of collaborative relationships between researchers and practitioners. This means, for example, that if research consortia are established, travel funds must be made available to enable close interactions between consortia members. It also entails supporting access to technical resources–such as CAE systems, CAE systems' (proprietary) representations, and industrial data sets–to academic as well as to industrial participants.

2. CONTENT AND CONTEXT

Many different kinds of facts can be recorded about a design and its development. A design system must specify the scope of the knowledge it captures. Using the terminology of Allen Newell, what is needed is a definition of the design record at the "knowledge level." This amounts to a theory of what information is to be recorded and how that information is going to be used. Such theory can be implemented by defining the structure of design knowledge bases and the tools which operate upon them. That theory must cover both technical content about the design and the context in which it evolved. The situation has parallels in the natural sciences; for example, to understand an animal (design artifact) one must also know its environment, physical and interpersonal. The full truth of this situation begins to be revealed in the work of [Tang89] and [Minneman *et al.*

91] who have studied designers at work and report, without ambiguity, that a large fraction of the knowledge about an artifact is actually held by the design team as a whole and no individual in particular.

Our expectation is that the coverage of knowledge bases capturing design will grow incrementally over time. The sequence of goals for this incremental growth includes (ordered by priority):

1. The final design artifact produced by the process.
2. The time at which various alternatives and partial designs were produced and by whom.
3. The criteria used for generating and selecting possible designs, when and by whom.
4. The traces of when and how each step in the design process was performed, the resources applied, and social context.

Access and use of the information in these knowledge bases will need to be supported by viewing and filtering mechanisms within the design environment. Research on design knowledge bases and on interaction support goes hand in hand.

Availability of this knowledge has a number of potential benefits. It enables concurrent design. It provides the information needed to determine which aspects of the design are critical and which can be varied, and to distinguish original commitments which must still be maintained from those which are no longer applicable. Information about assumptions, performance characteristics, boundary conditions, and the like could greatly facilitate design. Similarly, design reuse is made practical by enabling designers to determine the limitations and applicability conditions of candidates for reuse. The information could also be used for other purposes such as the semi-automated generation of manuals or other documentation. One benefit, however, must be realized before all others. The process of design capture must facilitate designing–it must reward the designer for participating in the knowledge elicitation process. In no area does this seem more immediate than in documenting designs, a task typically considered a necessary evil by many designers.

2.1 Near-Term (Quick Payoff) Issues in Content and Social Context

Work that could be accomplished within a one-to-two years time frame would provide both useful demonstrations and a supporting technical base for further work. The following near-term efforts that would produce compelling demonstrations and needed technology:

- *Expressing versions and levels of abstraction*. This entails extending existing representational formalisms to allow them to maintain multiple versions of a design and to keep track of relationships between those versions. It also entails extending them to maintain design descriptions at different levels of specificity and formality.

- *Sharing corporate knowledge through "war stories."* The opportunity exists using current technology to provide multimedia interfaces that allow organizations to record, index, and present case studies and lessons learned in a fashion that facilitates dissemination of that corporate experience to junior designers. The use of such material must be as *experiences*, not as lectures.

- *Indexing for retrieval of picture components and picture sets*. Pictorial information is extremely important to design. It is not satisfactory to merely have formal drawings on-line if it is not easy

for designers to associate them with informal sketches and photographic or video records of relevant content information. Tools are needed to facilitate entry of pictographic material into databases with annotations that can be used effectively as retrieval keys.

In addition to the above, two other near-term but more basic research efforts are needed to lay groundwork for further developments:

- *Empirical studies*. Collaborative research with social scientists on collecting factual information about team design in real-world settings is urgently needed (*e.g.*, [Ullman *et al*. 90]). Such research would serve to test and validate engineers' and computer scientists' hypotheses about design capture requirements, and to fuel generation of new hypotheses. In particular, the work of social scientists, however "interesting," may be of little use to engineers if it is not informed by our understanding of "real work" and computers. Findings from the field of computer supported cooperative work (*e.g.*, [CSCW88,90]) have many implications for design capture systems; these need to be explored and validated in the design domain.

- *Identifying an "ontology" of standardizable, knowledge-level conceptualizations*. This entails developing common approaches to describing key aspects of designs, *e.g*. geometry, requirements, rationale, and interdependencies.

2.2 Long-Term Issues in Content and Social Context

Over a longer term (three to five years) a number of more complex representational issues need to be addressed. These include:

- *Models of knowledge used over the product lifecycle*. Research is needed to extend design ontologies to capture knowledge needed for functions beyond manufacturing, *e.g*., training, maintenance, redesign, disposal, and so on. Initially, the goal would be to capture this additional knowledge for use within a design. Eventually, the goal is to index that knowledge so as to make it usable in other designs.

- *Aids for helping people understand, classify, organize and structure picture components and sets of pictures*. These aids would help in structuring databases of (formal) drawings to facilitate informed access (*e.g*., defining new indices) as well as in analyzing drawings to assimilate them into those structured databases. Informal sketches and visual records (*e.g*., photographs, video clips) are equally important but are mostly neglected by current studies.

- *Mechanisms to express the level of commitment to assertions (and changes in level over time)*. The issue is to maintain a representation of the status of team collaboration over design alternatives that more accurately reflects the status of the negotiation process, thereby helping to focus attention on topics requiring further consideration.

- *Mechanisms for representing, in distinguishable form, consensus commitments vs. beliefs of individual participants*. The goal, as above, is to provide a more detailed representation of the status of design discussions in a way that supports focus of attention on topics requiring further consideration.

3. MEDIA FOR ENTERING AND DISPLAYING DESIGN INFORMATION

A great deal of the information needed to understand a design is currently not available via computer. To capture knowledge about a design, we need to get at information currently exchanged via whiteboards, design notebooks, notes on napkins, conversations, gestures, snapshots of physical models, and many other mechanisms of everyday human communication. To retain that information and share it with others, it is necessary to get it into a machine in a structured form. At the minimum, the structure imposed on the information must be sufficient to make it retrievable for human use and presentable in understandable forms. It is far preferable, however, to get information into a machine in a form amenable to distillation and reorganization.

A key technical need, therefore, is the development of advanced techniques for accepting and interpreting multimedia input and for preparing and presenting multimedia output. For design capture to become feasible, it must not impose drag on the design process. Designers will only provide design information to machines when providing that information is a natural part of the communication process. In the absence of multimedia techniques, the burden of slowing down thought processes to match the machine media limitations is too great.

3.1 Near-term Issues in Media for Design Capture

The first steps in this direction, with potential benefits available within 1-2 years, involve preliminary steps toward combining particularly useful media. Coupled with these steps, we believe it is feasible to expect advances in the interpretation of particular kinds of input. Specifically, we advocate research and development focusing upon:

- *Integrated, recorded multi-media input*. An important next step consists of consolidating gains by enabling combinations of media to be recorded, indexed, stored, and retrieved (*e.g.*, voice annotations to text or diagrams). Annotated diagrams (photographs, video clips, scanned images) where pointing indicates a place or region being referenced and voice or text transmits the annotating information, are a particularly informative mechanism.

- *Multi-user identification*. Design specifications, in addition to being entered simultaneously through multiple input devices, may be entered by multiple individuals. Those individuals might be collaborating on producing a shared input, or they might each be creating separate inputs as contributions to a design discussion. Current work has demonstrated a number of mechanisms supporting multiple user interaction, but these are generally built on top of layers of software. Effective, high-performance realization of these techniques in a fashion that allows practical dissemination can only be achieved if recognition of the existence of multiple users is moved down to the systems-software level.

- *3D models from sketches*. Significant progress has been demonstrated in drawing programs allowing designers to interactively create two-dimensional sketches which the system interprets as a 3D synthetic structure [Hwang80]. Further improvements on the performance and flexibility of these systems will greatly enhance the ease with which designers can work.

- *Capturing information from voice and pen input devices*. The ability to record and interpret input via these two media is essential to increase the range of information that can be collected from

designers without impeding their flow of thought. Improvements in the speed of interpreting a wide range of handwritten entries are on the horizon. These developments need to be accelerated and made easy to access by the developers of design aids.

The result of these developments will be a layer of supporting technology which will enable construction of unobtrusive systems for designers. These tools should actually help them do what they do today and to leverage off three key advantages of the electronic medium: its ability to support asynchronous communication, anonymous communication, and automatic archive communication. Tools should help make the process of providing information to design systems a natural part of the design process rather than a burden.

All of the above involve consolidation and application of technology which is regarded as close to being ready today. While elements of the technology may be "familiar," this usage is novel and requires solid experimental validation. Using design applications as a forcing function for these technologies will hasten their development, will provide useful proofs of concept for design systems, and will improve our understanding of what is needed to help make computer-based design capture tools part of the natural ecology of designers.

3.2 Long-term Issues in Media for Design Capture

Over a longer term (three to five years) the research issues involve a transition *from passive recording and presentation* of multimedia information, *to active interpretation and construction.* Specific goals crucial to facilitating design capture and reuse include the following:

- *Integrated, interpreted multimedia input.* The goal is to accept inputs comprised of multiple media sources, and combine them in a single, unified interpretation. A particular compelling application of this technology is in using voice to clarify the interpretation of elements created while making a drawing (*e.g.*, in a mechanical modeling interface, telling the system verbally which interpretation to make of a line which could be seen as passing either in front of or behind a surface). Giving designers a medium that can "travel" with them is probably the most enabling step possible and could clarify which processes can and can not be supported "on the move" (See paragraph on "ubiquitous computing" below).

- *Visual languages supporting automated interpretation of drawings.* The goal is to develop standard graphical conventions and rules for combining picture elements that allow a system to parse a drawing into constituent components. Applications range from cleaning up rough, hand-drawn sketches to constructing models of electro-mechanical systems from the drawings. A related problem is to correlate drawings and handwriting using structured displays. The issue here is to extend visual languages to include conventions for indicating annotations and to integrate the interpretation of annotations expressed in handwritten form.

- *High-fidelity sketch and gesture capture.* Current drawing systems do not capture/interpret all of the information potentially available in a hand-drawn picture, such as the thickness of a line or the use of multiple colors. Furthermore, videotaped studies of designers at work show that they rely quite heavily on gestures to communicate information to each other about the drawings (*e.g.*, the scale of the drawing or the nature of motion for a device's moving parts) [Tang89][Bly88]. Capturing more detail about drawings and about both the gestures used to talk about them and the

gestures used to manipulate them, is an essential component of helping designers express early, informal visualizations.

- *Off-line understanding of handwritten documents*. The goal is to allow systems in batch mode to scan in lengthy handwritten documents and convert them to text strings.

As mentioned above, support for *ubiquitous computing* could have a substantial impact on unobstrusive design capture and reuse. Design is a social and intellectual process that takes place wherever designers are, not necessarily where their office equipment is. To capture design knowledge, computing capabilities must accompany the designers. Cellular technology makes it possible for small, powerful notebook computers to move with designers and still stay linked into the fully networked resources of their organization. Similarly, it has been demonstrated how sensors within an organization's facilities can provide the power to recognize individuals and move their computing environment with them as they roam throughout a building. Research is needed to perfect these technologies and apply them to bringing computing environments to designers rather than marching designers to the computer.

The end result of these research activities would be the technology for building fully integrated high-powered design notebooks, systems in which all of a designer's intermediate thoughts and activities on the way to a final design could be expressed conveniently.

4. PARADIGMS FOR ELICITATION AND COMMUNICATION

The next key issue concerns paradigms fostering the explicit expression of new or previously implicit concepts or structures. The techniques explored within this topic include methods both for actively encouraging and for passively facilitating the work of users in providing information and structuring it to get a comprehensive representation of the knowledge relevant to a design.

Advanced media are a necessary–but not sufficient–condition for effective computer-augmented design processes. Computerized media alone can affect *how* information is expressed but not *what* information is expressed. Thus, companion research is needed on how to design interactions between users and systems to promote rapid interchange of useful information. The research issues involve a range of techniques and questions. Solutions are required that recognize four characteristics of the design process. First, it involves multiple users with multiple points of views and objectives. Second, the information needed by users depends on their roles: some are designers, some are consultants on a particular aspect of a design, some are managers, and some are potential users. Third, those users may be geographically distributed rather than co-located. Fourth, those users may be attempting to communicate with the system and with each other via the system, either synchronously or asynchronously.

4.1 Near-term Issues in Paradigms for Elicitation and Communication

In the next 1-2 years of research and development, the emphasis should be on consolidating past research, and developing empirical data and data collection tools in order to guide further research.

In particular, we see a need for:

- *Tools for using design records to prepare briefings and guide de-briefings*. Work already accomplished or near completion indicates that it should be feasible to develop useful aids for assisting engineers in preparing presentations to managers about the status of design projects. Similarly, aids using even limited design records show potential to help in debriefing engineers moving off a project in order to transfer their experience to their replacement. Work toward these goals could lead to some effective demonstrations of the benefits of design capture systems. Also, because these tasks represent burdensome real-world demands on engineers, successful demonstrations would appeal to applied engineers.

- *Techniques for observing and analyzing design processes "in vivo"* (see references at the end of this report). Design of design capture systems today is largely driven by engineer's intuitions about how teams of designers do their work. The time has come to develop a corpus of knowledge on the subject, although the techniques required will come from fields like anthropology and sociology rather than the hard sciences more familiar to computer scientists and engineers. The development of test-bed environments for these studies would accelerate all aspects of research and development addressed in this report.

- *Development of methodology for cost/benefits and trade-offs analysis of design recording techniques*. A number of alternative approaches have been proposed and demonstrated. Tools and methodology for comparing them would lay important groundwork in refining agendas for long-term research. Thus, it is possible that these particular applications can be used as "wedges" to gain initial acceptance among user communities and thereby ease the way for later insertion of more advanced technology.

- *Use of design records to support design audits*. Another target for near-term demonstrations of promise lies in tools to support audits of designs with respect to critical issues. Records of the design process in such demonstrations would facilitate quick evaluations of the extent to which particular considerations had been taken into account.

4.2 Long-term Issues in Paradigms for Elicitation and Communication

Over the three to five year time frame emphasis needs to be split between work on enabling technology for building knowledge-acquisition systems, development of higher-level automated agents in the design process, and evaluation of paradigms implemented from those building blocks. Research is needed in order to:

- *Explore trade-offs between "real time" and post-processing in the structuring of inputs*. The question that needs to be better understood is: what sort of trade-offs will designers accept between immediacy of feedback and sophistication of results? Answering this question may require developing and experimenting with automated facilities based on models of the design process, the problem domain, or the negotiation process. An example of an opportunity for greater automation is the intelligent completion of inputs.

- *Investigate means of managing interplay between capture and privacy*. The flip side of detailed record keeping of design information and of retaining information which enables their attribution to particular individuals may have a chilling effect on the design process. There is the risk that fear of consequences from being identified will prevent designers from proposing innovative

ideas which risk failure and/or will prevent them from opposing strongly-supported but inferior ideas. Examples of issues to be explored: "off the record" activities, hiding *vs*. showing the role and status of participants in the design process, and whether the policy for linking participants into the process ought to favor attribution *vs*. anonymity.

- *Provide support for easily building user interfaces tailored to different types of users and activities*. Among issues that need to be taken into account are variations in experience and background among participants in a design project . We should also consider the possibility of using automated agents to generate feedback with respect to over- or under-specified constraints. Among the topics for such automated design critics are dimensions, tolerances, and standards violations.

- *Explore mechanisms for organizational learning*. The issue is the conservation and evolution of corporate knowledge bases which allow transfer of experience between designers and related projects.

5. COMPUTER REPRESENTATION AND ENABLING TECHNOLOGIES

In what form(s) does the machine express and store captured information for internal manipulation and external communication? Without research on the nature of the information repository, powerful and effective systems for design knowledge capture will not scale up to practical design problems, nor will they evince the flexibility and usability that are required. Furthermore, work is needed to understand and develop the information infrastructures and resources. In the research community, there is a need for sharing information to facilitate design research and for facilitating creation of bigger systems by composing the results of individual research projects. In the applied community, there is a need for corporate information infrastructure to support communication and exchange of information between design process participants.

5.1 Near-term Issues in Internal Representation and Enabling Technologies

In the one-to-two-year time frame infrastructure issues primarily concern consolidation and dissemination of technology. There is a need to provide researchers with access to the next generation of computing power, both hardware and software. This means:

- *Corpus of design-process records made available to researchers*. A near-term requirement is the development of common testbed problems facilitating comparison of research efforts. Having a small number of shared "E. Coli" design tasks would provide a common base for discussion in evaluating alternative approaches. Furthermore, as long as the corpus is updated to reflect evolution in the understanding of the form and content of design records, it would serve as a mechanism to help researchers attend to interoperability across sites.

- *Mobile, personal, high-performance computing*. Design capture systems need to start being built upon notebook, not desk-top-sized workstations.

- *Design-oriented next-generation data/knowledge-bases*. Database, object base, and rule-based technologies need to be made accessible in a unified package, preferably with reasonably high commonality throughout the community. Design-oriented databases must give equal weight to textual and pictographic information [Lakin *et al*. 89].

5.2 Long-term Issues in Internal Representation and Enabling Technologies

Over the longer term, three to five years, the main focus should be to achieve significant improvements in knowledge representation technology. The outcome of this research will be the technology underlying a corporate information store of design knowledge. This store will support integrating, and cross-referencing at multiple levels of formality, several different kinds of data:

- Digitized data (pictures, hand-writing, audio, video).
- Semi-formal representations (hypermedia, semi-structured notes).
- Formal representations (knowledge bases, relational databases, and object-oriented databases).

Semiformal systems capture as much information as is appropriate in a form that can be processed automatically and facilitate capturing additional information in a form that people can understand, even if their machine cannot [Malone 89]. Semiformal representations will play a substantial role in empirically-driven research on design capture.

Key research goals are:

- *Modular architecture for design capture systems*. Certain fundamental requirements exist for any system. It is highly desirable to facilitate development of specialized systems by providing an architecture which can be used to implement the system. However, it is also desirable that this architecture be modularized so that researchers can replace a generic component with their own specialized implementation if need be. Among the essential modules: multi-user interfaces, hooks for user invoked tools, and autonomous design agents.
- *Support for multiple representations*. Different aspects of the design are best captured in different representations (*e.g.*, feature-based *vs.* geometric models of shapes). There is a need to support translation between them, caching of multiple representations, and dealing with coordination and consistency maintenance.
- *Providing the ability to represent fuzzy, incomplete, and difficult concepts*. These include a wide range of different problems, for example: geometry, product requirements, degrees of validity, commitments, and alternatives.
- *Development of an application programming interface for a virtual repository.* The design knowledge base should appear to be seamless to the services within the development environment.

6. CONCLUSIONS

We recommend that the development of aids for design capture be driven by real needs. Research should be conducted in collaboration with the end users of design capture tools. We expect interdisciplinary collaborations focused on understanding needed methodologies, not just generating new technologies. In doing so, the empirically-driven approach we advocate is intended to encourage researchers to look for leverage points where intervention in the design process will have maximum benefit. New technologies will be developed as a side effect of this work, but a lot is to be gained from applying current technology wisely.

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